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Abstract

Research performed by the ASCE Hydraulics Division - Task Committee on Alternatives for Overtopping Protection for Dams includes the investigation of innovative spillway designs. This paper briefly describes the design and construction of labyrinth spillways, fuseplug embankments, and flexible membrane spillways. A more detailed discussion will be included in the final report of the Task Committee.

Introduction

The majority of dam safety deficiencies identified in the United States in recent years consist of inadequate spillway capacity for passage of new design floods up to the probable maximum flood (PMF). The passage of large floods through undersized spillways can result in overtopping failure of the dam, with potential loss of life and significant downstream damages. Hydrologic studies and assessments of both the threat to life and potential economic losses are used to establish the design flood. Safe passage of the design flood may require increased spillway capacity, increased reservoir storage, overtopping protection, or some combination of these approaches.

Increased spillway capacity is achieved by increasing the spillway crest length, the discharge coefficient, or the operating head. The operating head for a given spillway can be increased by lowering the spillway crest and installing gates, or by raising the dam crest to permit higher reservoir levels. A modest increase in the discharge coefficient can generally be realized by refinements to the spillway crest shape and by channel improvements. A more common modification, however, is enlargement of the existing spillway or construction of a new spillway to increase the total spillway crest length.

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The type of spillway selected for design is primarily dependent upon site conditions and release requirements. The dam abutments may be suitable for enlargement of the existing spillway or construction of a new spillway. An existing saddle or depression along the reservoir rim leading to a natural waterway may be an ideal site for a new auxiliary-type spillway. The dam may be considered to provide a foundation for a new spillway or for overtopping protection. Gated spillways may be considered where their operation can be ensured through onsite attendance and proper maintenance, although uncontrolled crests are often seen as being more economical and reliable. Energy dissipation of spillway releases entering the downstream waterway may be provided by a roller bucket or hydraulic-jump stilling basin at the end of a conveyance structure (open chute or conduit), or by a plunge pool below an elevated flip structure. For lower heads, the energy dissipation may be provided within the chute itself by the use of concrete baffle blocks or concrete steps.

More innovative approaches to spillway designs have been developed in recent years to address dam safety concerns at a lower cost. Risk-based decision analyses have been used to establish justification for design floods less than the full PMF, and for assumption of greater risk. Spillway designs expected to sustain some damage during the passage of infrequent floods include an estimated annual risk cost based on the probability of damage and associated repair or replacement cost, but normally have a significantly lower construction cost. Three types of innovative spillways summarized below are labyrinth spillways, fuseplug embankments, and flexible membrane spillways.

Labyrinth Spillways

An effective method to increase the spillway crest length without an associated increase in structure width is to use a labyrinth weir. The labyrinth weir consists of a series of relatively slender walls having a repeating planform shape, generally triangular or trapezoidal, each with a vertical upstream face and a steeply sloping downstream face. The increased crest length provided by the walls allows the passage of greater discharges for a given structure width and operating head. Labyrinth spillways are particularly suited to sites where the spillway width and upstream water surface elevations are limited and larger discharges are required. A labyrinth spillway may also provide additional reservoir storage capacity in lieu of a more costly gated structure, while matching the original spillway discharge.

Factors affecting labyrinth spillway performance are structure geometry, fluid properties, and flow conditions. The plan geometry for one trapezoidal cycle is completely defined by the cycle crest length, ℓ, the cycle width, w, and either the sidewall angle, α, the wall length, B, or one-half the length of the apex, A. The apex half-length is commonly used in dimensional analysis, rather than the sidewall angle or wall length. The section geometry for the weir is defined by the upstream wall height, P, the downstream wall height, D, the wall thickness, T, and the crest radius, R. The independent flow variables are the total upstream head, H_o, and the downstream piezometric head, H_d. These variables are shown in figures 1 and 2. Fluid properties are adequately defined by the gravitational acceleration, g, with minor viscous and surface tension effects neglected.

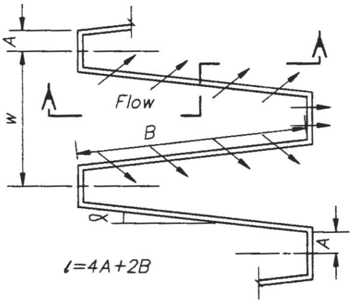

Figure 1. Plan View

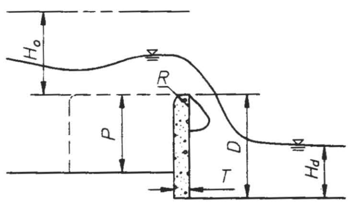

Figure 2. Section

Except for small upstream heads, increases in discharge over labyrinth weirs are not proportional to increases in crest length, but rather are determined by the complicated flow patterns within the upstream and downstream channels of each cycle. As the upstream head increases, the flow passes sequentially through fully aerated, partially aerated, transitional, and suppressed phases, with resulting reductions in discharge coefficient. Assuming a sharp-crested weir with a constant wall height and no tailwater effects, the discharge per unit cycle, Q_c, may be expressed as:

$$Q_c = C\ w\ H_o^{1.5}\ g^{0.5} \qquad (1)$$

with the discharge coefficient, C, a function of ℓ/w, w/P, and H_o/P. The cycle width is used as the characteristic length since the total width, W, is usually known. Design curves defining the discharge coefficients for labyrinth weirs have been developed by the Bureau of Reclamation (Lux III and Hinchliff, 1985). Approach and entrance losses will reduce the weir coefficients between 5 and 8 percent under good conditions, and up to 18 percent under poor conditions.

Labyrinth spillways are typically designed for H_o/P ratios between 0.45 and 0.55 to avoid operation in the suppressed phase and to minimize labyrinth size, although H_o/P ratios up to 0.9 have been proposed. Crest wall heights, P, up to 5 m can generally utilize a thin-walled cantilever section, with wall heights up to 15 m requiring thicker, gravity sections. For initial sizing of the weir, a vertical aspect ratio, w/P, of 2.5 is recommended. The apex ratio, A/w, should be held to the minimum required for construction, generally 0.0765 or less. Length magnification ratios, ℓ/w, up to 4 should be considered for H_o/P values up to 0.5. Other types of weirs may be more economical for length magnifications less than 2.

The downstream channel should be designed to maintain the tailwater at or below the weir crest during maximum discharge, minimize cross-waves, and provide nominal freeboard.

Only 5 labyrinth spillways were constructed worldwide before 1970, and only 10 before 1980. Since 1980, at least 18 additional projects have been constructed or proposed. The recent development of design curves and the continued operation of existing projects should result in greater consideration of labyrinth spillways in the future.

Fuseplug Embankments

Fuseplug embankments are typically located within an auxiliary spillway channel, and are designed to wash out in a predictable and controlled manner when additional spillway capacity is required, producing a deeper channel for higher operating heads on the auxiliary spillway crest or grade sill. As for other auxiliary-type spillways, fuseplug embankments are generally designed to operate for floods having return periods of 100 years or more. When a wide auxiliary spillway is required, the fuseplug can be divided into smaller sections using concrete walls, with each section constructed to a different elevation for operation at successively higher water surfaces. The entire fuseplug would therefore not wash out unless the full capacity of the spillway was required.

A fuseplug is designed as a zoned earth and rockfill embankment with a sloping impervious core. The core is inclined so that as the downstream materials wash away, pieces of the core will break off under gravity loads and be carried away with the flow. A sand filter should be provided around the core to prevent piping of the finer silt or clay materials from cracks which may develop within the core. The compacted sand and gravel zones are designed to be noncohesive and easily erodible once the washout process begins. Slope protection and gravel surfacing for the crest complete the typical fuseplug embankment section shown in figure 3. A pilot channel is typically provided within the embankment, having a crest 0.9 m lower than the fuseplug crest for 0.3 m of overtopping depth to initiate the breach and 0.6 m of freeboard. The outer zones for the pilot channel section are composed of slightly larger rockfill and fewer sand sizes to ensure a rapid break.

The erosion mechanics of fuseplug embankments were studied by the Bureau of Reclamation in 1983. The rate at which the fuseplug washes out is of primary importance, and depends upon the fuseplug geometry, the depth of flow, and the gradation and compaction of the embankment materials. Based on 1:10 and 1:25 scale model tests, the lateral erosion rate, ER, in meters per hour, for a fuseplug having the relative dimensions shown in figure 3, is dependent upon the embankment height, H, in meters, as follows:

$$ER = 13.2\ H + 46 \qquad (2)$$

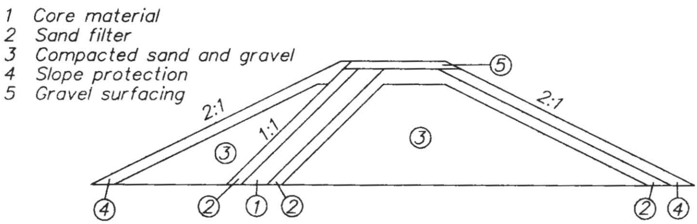

Figure 3. Embankment Section

This erosion rate is for fuseplugs ranging from 3 to 9 m high, having a downstream shell of sand and gravel compacted to 70 percent relative density, and a pilot channel located at one end with a width at least one-half the fuseplug height. Location of the pilot channel in the middle of the fuseplug embankment will result in the erosion rate occurring in both directions, with complete washout in about one-half the time. Adjustments to the erosion rate for other flow conditions or cross sections should be made using reference 2 (Pugh, 1985).

Following washout of the fuseplug, the discharge through the auxiliary spillway channel is determined by the channel width and the reservoir head. The spillway crest or grade sill is typically set at or above the normal reservoir water surface to avoid loss of storage capacity after washout of the fuseplug. A discharge rating curve can be developed by assuming control at the grade sill and estimating approach channel losses using backwater profile computations. Flow velocities through the channel must be sufficient to carry the eroded fuseplug materials downstream to avoid clogging.

Fuseplug embankments have been designed and constructed for numerous projects worldwide, including mine tailing dams, levees, and auxiliary spillways for dams. Model studies and a prototype test for the Oxbow Project in 1959 have shown that fuseplug embankments can be designed to wash out at a predictable rate when overtopped. Adjustment of the embankment materials or cross section, relocation of the pilot channel, or sectioning by divider walls may be required to limit the rate of increase in reservoir outflow during washout to an acceptable level. Flood routings play an important role in selecting these parameters for final design. Economic analyses should consider the probability of operation and the associated reconstruction cost.

Flexible Membrane Spillways

A flexible membrane lining has been shown to be a low-cost alternative to a concrete lining for auxiliary spillways on low-head structures. Studies initiated by the Bureau of Reclamation in 1981 resulted in the successful construction and operational testing of a flexible lining for an auxiliary spillway at Cottonwood Dam No. 5 in western Colorado (Timblin Jr., et al, 1988). The membrane was placed within an excavated channel and covered with a noncohesive soil layer. The soil layer washes away at the beginning of spillway operation, and the impermeable membrane lining carries the flow, protecting the foundation from erosion.

The membrane must have long-term durability and resistance to damage from hydraulic forces and debris during operation. Important material properties include tensile strength and flexibility, puncture and abrasion resistance, impact tear resistance, weatherability, and resistance to bacteria and fungus. Suitable lining materials include fabric-reinforced materials such as Hypalon, and high-density polyethylene (HPDE). A 36-mil Hypalon material was used for the field installation and testing.

The membrane-lined spillway channel for Cottonwood Dam No. 5 is 79 m long, with a 6.4 m drop, 3.7 m bottom width, 2:1 side slopes, and a maximum channel slope of 0.170. Concrete grade sills were provided at the upstream end for flow control and to prevent piping, and at the downstream end to prevent headcutting. Each membrane sheet overlaps the adjacent downstream sheet by 1.5 m, to provide a positive seal for water flowing down its surface while allowing relief of any hydrostatic pressures beneath the lining. By not bonding the sheets, transfer of hydraulic stress from sheet to sheet during operation is prevented. The edges of the liner sheets along the sides and at the upstream end were placed in trenches and backfilled with compacted soil. Loose, granular material (maximum size 20 mm) was placed to a depth of 0.15 m over the membrane for protection. Energy dissipation of spillway flows is provided by a natural hydraulic jump over riprap placed in the downstream channel.

An operational test was conducted in July 1986, producing a maximum discharge of 0.7 m^3/s and maximum flow velocities from 6 to 8 m/s, with an estimated Manning's n value of less than 0.015. Although the flow carried stones and cobbles up to 0.10 m in diameter, little or no damage to the membrane was observed. A small tear was attributed to a sharp stone found protruding from the subgrade. Long-term studies on this installation are continuing.

Appendix - References

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